

A quasi-periodic oscillation in the blazar J1359+4011

O. G. King,¹★ T. Hovatta,¹ W. Max-Moerbeck,² D. L. Meier,³ T. J. Pearson,¹
A. C. S. Readhead,¹ R. Reeves,¹ J. L. Richards⁴ and M. C. Shepherd¹

¹California Institute of Technology, 1200 E California Blvd, MC 249-17, Pasadena, CA 91125, USA

²National Radio Astronomy Observatory, PO Box 0, Socorro, NM 87801, USA

³NASA Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena, CA 91109, USA

⁴Department of Physics, Purdue University, West Lafayette, IN 47907, USA

Accepted 2013 September 4. Received 2013 September 4; in original form 2013 August 28

ABSTRACT

The Owens Valley Radio Observatory 40-m telescope has been monitoring the 15-GHz radio flux density of over 1200 blazars since 2008. The 15-GHz light curve of the flat spectrum radio quasar J1359+4011 shows a strong and persistent quasi-periodic oscillation. The time-scale of the oscillation varies between 120 and 150 d over an ~ 4 year time span. We interpret this as the active galactic nucleus mass-scaled analogue of low-frequency quasi-periodic oscillations from Galactic microquasars or as evidence of modulation of the accretion flow by thermal instabilities in the ‘inner’ accretion disc.

Key words: accretion, accretion discs – galaxies: active – galaxies: individual: J1359+4011 – galaxies: jets.

1 INTRODUCTION

Quasi-periodic behaviour in blazars at radio wavelengths occurs on time-scales of the order of years. It usually takes the form of periodic flaring, for instance, in the BL Lacertae object OJ 287 (1.12 or 1.66 yr; Hughes, Aller & Aller 1998), BL Lac itself (~ 2 and ~ 8 yr; Stirling et al. 2003; Villata et al. 2004) and AO 0235+16 (~ 5 or ~ 8 yr; Raiteri et al. 2001, 2006). This behaviour is usually explained by processes related to the orbital dynamics of the disc/jet system, such as periodically varying Doppler beaming from a precessing jet (Marscher & Gear 1985; Camenzind & Krockenberger 1992; Abraham 2000; Caproni, Abraham & Monteiro 2013) or processes related to the innermost stable orbit of the accretion disc (Broderick & Loeb 2006; Pihajoki, Valtonen & Ciprini 2013).

While quasi-periodic oscillations (QPOs) in the X-ray emission of stellar-mass black hole binaries are a common and well-studied phenomenon (Remillard & McClintock 2006), corresponding behaviour from supermassive black holes at the heart of active galactic nuclei (AGN) is very rare. Only one X-ray QPO from an AGN – the narrow-line Seyfert 1 galaxy REJ 1034+396 – has been reliably measured (Gierliński et al. 2008; González-Martín & Vaughan 2012). It has a period of ~ 1 h and is thought to be the mass-scaled equivalent of high-frequency QPOs seen in stellar black hole binaries (Middleton & Done 2010).

In this Letter, we describe the discovery of a remarkable and persistent QPO in the 15 GHz light curve of the flat-spectrum radio quasar (FSRQ) CGRABS J1359+4011. The source J1359+4011

($13^{\text{h}}59^{\text{m}}38^{\text{s}}.1$, $+40^{\circ}11'38''.3$ J2000) is a high Galactic latitude ($b = 70.8$) FSRQ (Landt et al. 2001; Sowards-Emmerd et al. 2005) at a redshift of $z = 0.407 \pm 0.001$. It has been detected at X-ray energies using *ROSAT* (Landt et al. 2001), but it is not visible at γ -ray energies and has not been included in either of the *Fermi* catalogues (Abdo et al. 2010; Nolan et al. 2012). J1359+4011 is thought to contain a $10^8 M_{\odot}$ black hole with high Eddington ratio accretion (Table 1). The data are described in Section 2, the QPO is explored using a wavelet decomposition in Section 3, and we interpret the QPO in Section 4 as being either the AGN analogue of low-frequency QPOs (LFQPO) or as being caused by thermal instabilities in the ‘inner’ accretion disc.

2 DATA

The 40-m telescope of the Owens Valley Radio Observatory (OVRO) is being used to monitor the 15-GHz flux densities of over 1200 active galaxies twice a week. This programme has been running continuously since 2008. The data are reduced and calibrated to form regularly updated light curves that are made available on the internet.¹

The OVRO 40-m receiver uses an alternation of two beams on the source (Readhead et al. 1989) to remove the varying atmospheric emission and diffuse background emission from the source flux-density measurement. The data are calibrated and the flux-density scale is set using the primary calibrator 3C 286, as described in Richards et al. (2011).

★ E-mail: ogk@astro.caltech.edu

¹ <http://www.astro.caltech.edu/ovroblazars/>

Table 1. The properties of J1359+4011 from D’Elia, Padovani & Landt (2003). The mass was determined using the H β emission line and the luminosity calculated in the interval $7.08 \times 10^{14} - 7.24 \times 10^{14}$ Hz.

$\log M_{\bullet}$ (M_{\odot})	$\log \dot{M}$ ($M_{\odot} \text{ yr}^{-1}$)	$\log \left(\frac{L}{L_{\text{Edd}}} \right)$	$\log \left(\frac{L_{\text{th}}}{L_{\text{tot}}} \right)$	$\log L_{\text{tot}}$ ($\text{erg s}^{-1} \text{ Hz}^{-1}$)
8.0	-1.7	-1.6	-1.7	30.03

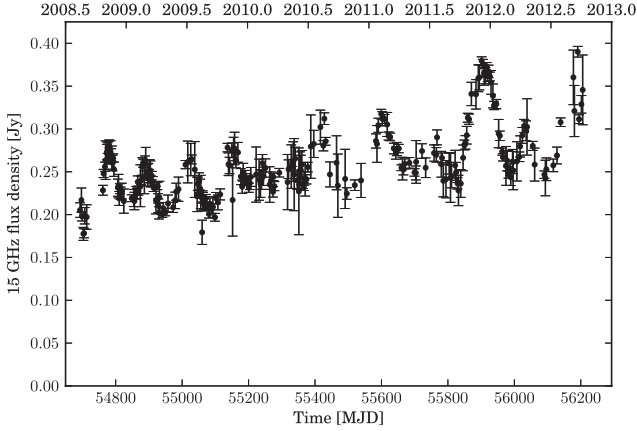


Figure 1. The OVRO 15-GHz light curve for J1359+4011. The data cover a 4.1 yr time span and show a strong quasi-periodic modulation (Fig. 2).

The 4.1 yr light curve of J1359+4011 is shown in Fig. 1. The object has been observed slightly more often than once a week, on average, with occasional gaps in the light curve due to telescope maintenance or poor weather. A modulation of about 25 per cent of the flux density is visible. This is the only source in the OVRO catalogue to show such a strong and persistent modulation.

Two instrumental effects would produce such a modulation of the light curve. The first is related to the dual-beam measurement process. If the reference field around the target source were to contain a patch of bright emission, this might produce elevation-dependent flux-density measurements. However, the data show no dependence of the flux density on elevation. The second systematic effect that might cause the modulation is linked to the pointing procedure used by the OVRO 40 m telescope. The sky is divided into 134 regions and pointing corrections for the 40-m telescope are calculated in each region. Time-dependent errors in the pointing correction for the region around J1359+4011 would result in a modulated light curve. Sources that share the same pointing correction would share the same fractional flux-density modulation. However, a careful study of the sources that share the same pointing correction shows that they contain no such common modulation. We conclude that the modulation seen in the J1359+4011 light curve is intrinsic to the source.

3 QUASI-PERIODIC BEHAVIOUR

Wavelets are an ideal tool for measuring quasi-periodic fluctuations. The data are decomposed into *localized* functions, which is preferable to Fourier analysis when searching for short-lived fluctuations or fluctuations with a varying period. Foster (1996) introduced an alternative to the discrete wavelet transform, the weighted wavelet Z-transform (WWZ), that is better suited to discovering the time-scale of fluctuations in the light curve and is robust against missing data. It is based on the Morlet wavelet (Grossmann & Morlet 1984) and has become a much-used tool in fields as diverse as pa-

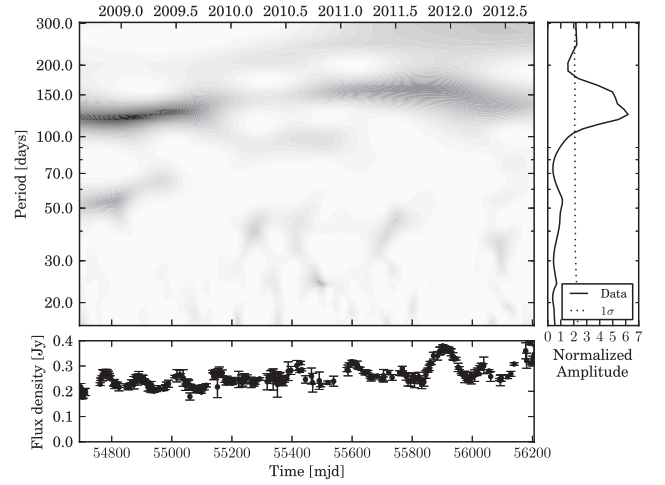


Figure 2. The WWZ of the light curve for the source J1359+4011, with darker colour indicating a stronger signal. A strong signal is seen throughout 2008 and most of 2009. It appears to fade in strength and increase in duration before returning in late 2011. The WWZ amplitude has been normalized as described in the text; the global wavelet in the right-hand panel includes the 1σ significance contour determined from Monte Carlo simulations.

leoceanography (Incarbona et al. 2010), climate change (Johnson 2010), pulsating variable stars (Templeton & Karovska 2009) and AGN variability (Hovatta, Lehto & Tornikoski 2008). The values that the WWZ takes can be thought of as goodness-of-fit parameters similar to the familiar chi-square statistic.

We used Monte Carlo simulations to establish the statistical significance of the structures in the WWZ of the light curve. The null hypothesis is that the light curve is a Gaussian random process with power-law power spectrum. We generated artificial light curves with the same power spectral density slope of 1.5 as J1359+4011 using a modified implementation of Uttley, McHardy & Papadakis (2002), as described in Max-Moerbeck et al. (in preparation). The artificial light curves had the same variance and sampling as the data. We used 1000 artificial light curves to establish the mean and standard deviation of the WWZ at each point in the period/time plane for the artificial data. The WWZ of J1359+4011 is shown in Fig. 2. The amplitude has been normalized by the mean established through Monte Carlo simulations. The average wavelet over time in the right-hand panel includes the 1σ contour.

The wavelet analysis reveals an initial ~ 120 d oscillation in 2008/2009 that then fades in amplitude and increases in period, reaching minimum amplitude in mid-2010. It then increases in amplitude and peaks at a period of ~ 150 d in early 2012. The range of detectable time-scales is from 15 to 300 d.

4 INTERPRETATION

A variety of mechanisms have been proposed to explain periodic behaviour in blazar radio and optical emission. These include periodically varying Doppler beaming from a precessing jet (Marscher & Gear 1985; Camenzind & Krockenberger 1992; Abraham 2000; Caproni et al. 2013) and processes related to the innermost stable orbit of the accretion disc (Broderick & Loeb 2006; Pihajoki et al. 2013). The periods observed are generally on time-scales of the order of years.

One possible explanation for the behaviour of J1359+4011 is that the oscillation is a direct analogue of the QPOs seen in micro-quasars (jet-producing black hole X-ray binaries). Since many black

hole time-scales vary approximately inversely with black hole mass, scaling the oscillation in J1359+4011 in this manner to a $10 M_{\odot}$ black hole would result in a QPO of a few hertz – squarely in the range of an LFQPO for a typical microquasar. LFQPOs in the latter sources are usually classified as types A, B or C (Casella, Belloni & Stella 2005). The closest analogue of the oscillation in J1359+4011 may be the type-A QPO, which is associated with high Eddington ratio accretion² and low Q ($v/\Delta v$). Type-A QPOs also have low fractional variability (only a few per cent), but that measurement is performed in the X-ray; very high time resolution radio studies have not yet been done on QPO-producing microquasars, so no comparable radio variability values exist yet. In principle, one might be able to verify the expected low variability by observing J1359+4011 in the X-ray, but given past problems in finding X-ray QPOs in AGN (not to mention the possible beamed jet contamination of the X-ray flux in this blazar), such an observation would be very difficult. Furthermore, the currently popular model for classical microquasar QPOs (particularly types A and C) is Lense–Thirring precession of a geometrically thick, accretion torus near the central black hole (Ingram, Done & Fragile 2009; Ingram & Done 2011; Motta et al. 2011). Such models even predict the X-ray flux/QPO frequency correlations seen in type-C QPOs. If this torus precession would slightly precess the pointing direction of the J1359+4011 blazar’s jet, this model may account for the radio oscillations seen in Fig. 1.

Another potential explanation for the observed QPO is an instability in the disc/jet system. Magnetically choked accretion flows (MCAFs) in general-relativistic three-dimensional magnetohydrodynamic simulations are seen to produce quasi-periodic fluctuations in the energy outflow efficiency of the relativistic jet close to the black hole (Tchekhovskoy, Narayan & McKinney 2011). The dominant mode of these fluctuations has a period of $\sim 70 r_g/c$ for a rapidly spinning black hole ($a = 0.9375$), which is ~ 1 d when the Schwarzschild radius $r_g \simeq 3 \times 10^{11}$ m for a $10^8 M_{\odot}$ black hole. Slower-spinning black holes are expected to have longer periods (McKinney, Tchekhovskoy & Blandford 2012). The different time-scale makes it improbable that MCAFs are the mechanism behind the QPO seen in the J1359+4011, assuming that it is even possible for the MCAF QPOs to radiatively transfer out to the optically thin radio region of the jet. The so-called dynamo cycles (Brandenburg et al. 1995) in simulations of black hole accretion discs – oscillations in the azimuthal magnetic field above the accretion disc – have periods of $\sim 5000 s GM_{\bullet}/c^3$ (O’Neill et al. 2011) which is ~ 30 d for a $10^8 M_{\odot}$ black hole. It is unclear, however, whether these oscillations can produce an observable signature in the radio jet.

A third possible model that would be applicable only to high Eddington ratio black hole systems involves an instability in the accretion flow that would alternately feed and starve the black hole with accreting material. This is the Lightman–Eardley secular (accretion flow) instability, in which the entire radiation-pressure-dominated ‘inner’ region of the accretion disc behaves in a manner opposite to that normally expected: the accretion rate varies *inversely* with vertically integrated disc surface density (Lightman & Eardley 1974). The accretion flow then breaks up into rings of high surface density (which accretes slowly internally) and low surface density (which accretes rapidly internally). The time for the

entire radiation-pressure-dominated disc region to empty [$12 \text{ min } (M_{\bullet}/10 M_{\odot})^{4/3} (\dot{m}/0.3)^{2/3}$] is much too long (9000 yr for a $10^8 M_{\odot}$ black hole accreting at $\dot{m} \sim 0.025$; Meier 2012) to explain the J1359+4011 oscillations. However, if the disc rings formed via thermal processes, then when they initially form at or near the outer edge of the ‘inner’ disc region each would accrete towards the black hole, separated roughly by the thermal time at or near that outer edge. The thermal time-scale at the outer edge of the ‘inner’ disc region is $\sim 1 \text{ s } (M_{\bullet}/10 M_{\odot})^{8/7} (\dot{m}/0.3)^{8/7}$, or ~ 0.2 yr. Given the uncertainty in the coefficients and black hole mass in these expressions (factors of 2–3), this is in rough agreement with the observed 0.3–0.4 yr oscillation period in J1359+4011.

5 CONCLUSIONS

The 15-GHz light curve for the FSRQ J1359+4011 shows a strong QPO with a period that varies between 120 and 150 d. The fluctuations in the light curve are intrinsic to the source and are not due to instrumental or observing effects. It is the only source in the OVRO catalogue of over 1200 sources to show such a strong and persistent QPO.

The physical cause of this QPO is unclear. The QPO period is of the right time-scale to be the AGN analogue of LFQPOs observed at X-ray energies in stellar-mass black hole binaries. If this is the case, the precessing thick torus (that is thought by some authors to be the origin of the X-ray QPOs in black hole binaries) may be precessing the direction of the blazar jet slightly, thereby modulating the radio light curve.

Another possible explanation for the modulation of the jet luminosity is instabilities in the accretion flow. Inwardly accreting rings caused by the Lightman–Eardley secular instability would be separated by the thermal time-scale measured at the outer edge of the ‘inner’ disc region. This time-scale is of the right order to explain the oscillation period in J1359+4011.

ACKNOWLEDGEMENTS

We thank Russ Keeney for his support of observations at OVRO. The OVRO 40-m programme is supported in part by NASA grants NNX08AW31G and NNX11A043G and NSF grants AST-0808050 and AST-1109911. TH was supported by the Jenny and Antti Wihuri foundation. Support from MPIfR for upgrading the OVRO 40-m telescope receiver is acknowledged. We thank V. Pavlidou for useful discussions. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

- Abdo A. A. et al., 2010, *ApJS*, 188, 405
- Abraham Z., 2000, *A&A*, 355, 915
- Brandenburg A., Nordlund A., Stein R. F., Torkelsson U., 1995, *ApJ*, 446, 741
- Broderick A. E., Loeb A., 2006, *MNRAS*, 367, 905
- Camenzind M., Krockenberger M., 1992, *A&A*, 255, 59
- Caproni A., Abraham Z., Monteiro H., 2013, *MNRAS*, 428, 280
- Casella P., Belloni T., Stella L., 2005, *ApJ*, 629, 403
- D’Elia V., Padovani P., Landt H., 2003, *MNRAS*, 339, 1081
- Foster G., 1996, *AJ*, 112, 1709
- Gierliński M., Middleton M., Ward M., Done C., 2008, *Nat*, 455, 369

² Here we define ‘high Eddington ratio’ as an accretion ratio $\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$ at which, in standard thin disc theory, the disc ‘inner’ region is expected to be radiation pressure dominated. For $M_{\bullet} = 10 M_{\odot}$, this is $\dot{m} \gtrsim 0.15$ and for $M_{\bullet} = 10^8 M_{\odot}$, a high Eddington ratio would be anything above $\dot{m} \gtrsim 0.02$.

- González-Martín O., Vaughan S., 2012, A&A, 544, A80
- Grossmann A., Morlet J., 1984, SIAM J. Math. Anal., 15, 723
- Hovatta T., Lehto H. J., Tornikoski M., 2008, A&A, 488, 897
- Hughes P. A., Aller H. D., Aller M. F., 1998, ApJ, 503, 662
- Incarbona A., Martrat B., Di Stefano E., Grimalt J. O., Pelosi N., Patti B., Tranchida G., 2010, Paleocyanography, 25, 2218
- Ingram A., Done C., 2011, MNRAS, 415, 2323
- Ingram A., Done C., Fragile P. C., 2009, MNRAS, 397, L101
- Johnson R. W., 2010, Ap&SS, 326, 181
- Landt H., Padovani P., Perlman E. S., Giommi P., Bignall H., Tzioumis A., 2001, MNRAS, 323, 757
- Lightman A. P., Eardley D. M., 1974, ApJ, 187, L1
- McKinney J. C., Tchekhovskoy A., Blandford R. D., 2012, MNRAS, 423, 3083
- Marscher A. P., Gear W. K., 1985, ApJ, 298, 114
- Meier D. L., 2012, Black Hole Astrophysics: The Engine Paradigm. Springer-Verlag, Berlin
- Middleton M., Done C., 2010, MNRAS, 403, 9
- Motta S., Muñoz-Darias T., Casella P., Belloni T., Homan J., 2011, MNRAS, 418, 2292
- Nolan P. L. et al., 2012, ApJS, 199, 31
- O’Neill S. M., Reynolds C. S., Miller M. C., Sorathia K. A., 2011, ApJ, 736, 107
- Pihajoki P., Valtonen M., Ciprini S., 2013, MNRAS, 434, 3122
- Raiteri C. M. et al., 2001, A&A, 377, 396
- Raiteri C. M. et al., 2006, A&A, 459, 731
- Readhead A. C. S., Lawrence C. R., Myers S. T., Sargent W. L. W., Hardebeck H. E., Moffet A. T., 1989, ApJ, 346, 566
- Remillard R. A., McClintock J. E., 2006, ARA&A, 44, 49
- Richards J. L. et al., 2011, ApJS, 194, 29
- Sowards-Emmerd D., Romani R. W., Michelson P. F., Healey S. E., Nolan P. L., 2005, ApJ, 626, 95
- Stirling A. M. et al., 2003, MNRAS, 341, 405
- Tchekhovskoy A., Narayan R., McKinney J. C., 2011, MNRAS, 418, L79
- Templeton M. R., Karovska M., 2009, ApJ, 691, 1470
- Uttley P., McHardy I. M., Papadakis I. E., 2002, MNRAS, 332, 231
- Villata M. et al., 2004, A&A, 424, 497

This paper has been typeset from a \LaTeX file prepared by the author.